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# Optimal Placement of Thyristor Controlled Series Capacitor to Reduce the Transmission Loss

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***Abstract:***

In the present day world power system deregulation is at its full stretch. In this deregulated environment ensuring that the power system operates with in its specified limits, which have been traditionally referred to as power system security is the most concerned aspect, which is currently being given at most importance. The term reliability depends on transmission loss. Maintaining the security and reliability is vital. Failures can result in widespread blackouts with potentially severe social and economic problems. Facts devices such as thyristor controlled series compensators and thyristor controlled phase angle regulators, by controlling the power flows in the network, can help to reduce the flows in heavily loaded lines resulting in an increased load ability of the network and reduced cost of production .This paper presents the development of simple and efficient models for optimal location of facts devices that can be used to reduce transmission losses by controlling their parameters optimally.

**Key words:** TCSC, FACTS.

## I. Introduction:

Over the years, it has become clear that the maximum safe operating capacity of the transmission system is often based on voltage and angular stability rather than on its physical limitations. So rather than constructing new lines, industry has tended towards the development of technologies or devices that increase transmission network capacity while maintaining or even improving grid stability. Many of these now established technologies fall under the title of FACTS [8] (Flexible AC Transmission Systems). They not only improve the capacity of power transmission systems, but flexibility is also greatly enhanced.

The FACTS is not a single high power controller, but rather a collection of controllers, which can be applied individually or in co-ordination with others to control one or more of the interrelated system parameters mentioned above. A well-chosen FACTS controller can overcome the specific limitations of a designated transmission line or a corridor. Because all FACTS controllers represent applications of the same basic technology, there production can eventually take advantage of technologies of scale. Just as a transistor is a basic element for a whole variety of micro-electronic chip and circuits, the thyristor or high power transistor is the basic element for a variety of high power electronic controllers.

The opportunities arising through the ability of FACTS controllers to control the inter-related parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle and the damping of oscillations at various frequencies below the rated frequency. These constraints cannot be overcome, while maintaining the required system reliability, by mechanical means without lowering the usable transmission capacity. By providing added flexibility, FACTS [3] controllers can enable a line to carry power closer to its thermal rating. Mechanical switching needs to be supplemented by rapid-response power electronics.

## II.Thyristor Controlled Series Capacitor (TCSC):

Thyristor Controlled Series Capacitors (TCSC) provides a proven technology that addresses specific dynamic problems in transmission systems. TCSC's are an excellent tool to introduce if increased damping is required when interconnecting large electrical systems. Additionally, they can overcome the problem of Sub-Synchronous Resonance (SSR), a phenomenon that involves an interaction between large thermal generating units and series compensated transmission systems.

TCSC in the present application is treated as the continuously varying capacitor whose impedance is controllable in the range [0, Xcmax], where Xc is the capacitive reactance. The controllable series capacitive impedance cancels the part of the series reactive line impedance resulting in reduced over all transmission impedance and correspondingly increased transmitted power.Thyristor controlled series compensator is actively controlled capacitive impedance which can affect only the

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magnitude of the current flowing through the transmission line. At any given impedance setting of the TCSC, particular line impedance is defined for which the transmitted power is strictly determined by the transmission angle. Therefore the reactive power demand at the end points of the line are determined by the transmitted real power in the same way as if the line was uncompensated but had lower line impedance. Consequently the relation between the real and the reactive power can be represented by the Q-P curve for the capacitance ranging from 0 to Xcmax.

**Static modeling of FACTS devices:**

Consider a Transmission line between buses i and j let the real and reactive power flow from bus-i to bus-j ($P_{ij}$ and $Q_{ij}$) can be written as [1]

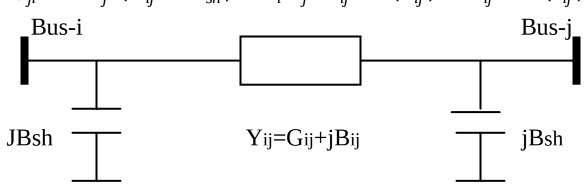
$$P_{ij} = -V_i^2 G_{ij} - V_i V_J [G_{IJ} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})\}$$

$$Q_{ij} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_J [G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})]$$

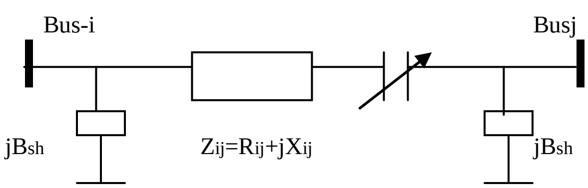
Where $\delta_{ij} = \delta_i - \delta_j$ similarly, the real and reactive power flow from bus-j to bus-i $(P_{ji} and Q_{ji})$ is

$$P_{ji} = V_j^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) - B_{ij} \sin(\delta_{ij})]$$

$$Q_{ji} = -V_j^2 (B_{ij} + B_{sh}) + V_i V_j [G_{ij} \sin(\delta_{ij}) + B_{ij} \cos(\delta_{ij})]$$




Model of transmission line




Model of TCSC

Consider the model of a transmission line [1] with a TCSC connected between bus-i and bus-j. During the steady state the TCSC can be considered as a static reactance $(-jx_c)$ .The real and reactive power flow from bus-i to bus-j. $(P_{ij}^c and Q_{ij}^c)$, from bus j-i $(P_{ji}^c and Q_{ji}^c)$ of a line having series impedance $z_{ij} (= r_{ij} + x_{ij})$ and a series reactance $(-jx_c)$ are

$$P_{ij}^c = V_i^2 G_{ij}^{'} - V_i V_j (G_{ij}^{'} \cos\delta_{ij} + B_{ij}^{'} \sin\delta_{ij})$$

$$Q_{ij}^c = -V_i^2 (B_{ij}^{'} + B_{sh}) - V_i V_j [G_{ij}^{'} \sin(\delta_{ij}) - B_{ij}^{'} \cos(\delta_{ij})$$

$$P_{ji}^C = V_j^2 G_{ij}^{'} - V_i V_j [G_{ij}^{'} \cos\delta_{ij} - B_{ij}^{'} \sin\delta_{ij})$$

$$Q_{ji}^c = -V_j^2 (B_{ij} + B_{sh}) + V_i V_j [G_{ij}^{'} \sin(\delta_{ij}) - B_{ij}^{'} \cos(\delta_{ij})]$$

The active power loss $(P_{Lk}^c)$ in line-k connected between bus-i and bus-j is

$$P_{Lk}^c = V_j^2 G_{ij}^c + V_j^2 G_{ij}^{'} - 2V_i V_j G_{ij}^{'} \cos\delta_{ij}$$

Where $G_{ij}^{'} = \dfrac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2} and B_{ij'}^{'} = \dfrac{-(x_{ij} - x_c)}{r_{ij}^2 + (x_{ij} - x_c)^2}$

The change in the line flow due to series capacitance can be represented as a line with out series capacitance with power injected at the receiving and sending ends of the line .The real power injections at bus-i $(P_{ic})$ and bus-j $(P_{jc})$ can be expressed, using above equations as

$$P_{ic} = V_i^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \sin\delta_{ij} + \Delta B_{ij} \sin\delta_{ij}]$$

$$P_{jc} = V_j^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos\delta_{ij} + \Delta B_{ij} \sin\delta_{ij}]$$

Similarly, the reactive power injections at bus-i $(Q_{ic})$ and bus-j $(Q_{jc})$ can be expressed as

$$Q_{ic} = -V_i^2 \Delta B_{ij} - V_i V_j [\Delta G_{ij} \sin\delta_{ij} - \Delta B_{ij} \cos\delta_{ij}]$$

$$Q_{jc} = -V_i^2 \Delta B_{ij} + V_i V_j [\Delta G_{ij} \sin\delta_{ij} + \Delta B_{ij} \cos\delta_{ij}]$$

Where

$$\Delta G_{ij} = \frac{x_c r_{ij} (x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$$

and

$$\Delta B_{ij} = \frac{-x_c (r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$$

## III. Load Flow Solution by Placing TCSC at Maximum Line Loss:

The TCSC power flow model presented in this section is based on concept of a variable series reactance [4], the value of which is adjusted to the power flow across the branch to a specified value .The changing reactance Xtcsc, shown in figures, represents the equivalent reactance of all the series-connected modules making up the TCSC, when operating in either the inductive or the capacitive regions.The transfer admittance matrix of the variable series compensator shown in Figure is given by

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} jB_{kk} & jB_{km} \\ jB_{mk} & jB_{mm} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix}$$

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For inductive operation, we have

$$B_{kk}=B_{mm}= -\frac{1}{Xtcsc}$$

$$B_{km}=B_{mk}= \frac{1}{Xtcsc}$$

And for capacitive operation the signs are reversed. The active and reactive power equation at bus k is:

$$P_k=V_kV_mB_{km}\sin(\theta_k-\theta_m)$$

$$Q_k= - V_k\text{^}2B_{kk} - V_kV_mB_{km}\cos(\theta_k-\theta_m)$$

For the power equations at bus m, the subscripts K and M are exchanged in Equations .In Newton Raphson solutions these equations are linearised with respect to the series reactance. For the condition shown in Figure where the series reactance regulates the amount of active power flowing from bus K to bus M at a value $P_{km}^{reg}$, the set of linearised power flow equations is:

$$\begin{bmatrix}\Delta P_k\\ \Delta P_m\\ \Delta Q_k\\ \Delta Q_m\\ \Delta P_{km}^{Xtcsc}\end{bmatrix}=\begin{bmatrix}\frac{\partial P_k}{\partial\theta_k} & \frac{\partial P_k}{\partial\theta_m} & \frac{\partial P_k}{\partial V_k}V_k & \frac{\partial P_k}{\partial V_m}V_m & \frac{\partial P_k}{\partial X_{TCSC}}X_{TCSC}\\ \frac{\partial P_m}{\partial\theta_k} & \frac{\partial P_m}{\partial\theta_m} & \frac{\partial P_m}{\partial V_k}V_k & \frac{\partial P_m}{\partial V_m}V_m & \frac{\partial P_m}{\partial X_{TCSC}}X_{TCSC}\\ \frac{\partial Q_k}{\partial\theta_k} & \frac{\partial Q_k}{\partial\theta_m} & \frac{\partial Q_k}{\partial V_k}V_k & \frac{\partial Q_k}{\partial V_m}V_m & \frac{\partial Q_k}{\partial X_{TCSC}}X_{TCSC}\\ \frac{\partial Q_m}{\partial\theta_k} & \frac{\partial Q_m}{\partial\theta_m} & \frac{\partial Q_m}{\partial V_k}V_k & \frac{\partial Q_m}{\partial V_m}V_m & \frac{\partial Q_m}{\partial X_{TCSC}}X_{TCSC}\\ \frac{\partial P_{km}^{X_{TCSC}}}{\partial\theta_k} & \frac{\partial P_{km}^{X_{TCSC}}}{\partial\theta_m} & \frac{\partial P_{km}^{X_{TCSC}}}{\partial V_k}V_k & \frac{\partial P_{km}^{X_{TCSC}}}{\partial V_m}V_m & \frac{\partial P_{km}^{X_{TCSC}}}{\partial X_{TCSC}}X_{TCSC}\end{bmatrix}\begin{bmatrix}\Delta\theta_k\\ \Delta\theta_m\\ \frac{\Delta V_k}{V_k}\\ \frac{\Delta V_m}{V_m}\\ \frac{\Delta X_{TCSC}}{X_{TCSC}}\end{bmatrix}$$

Where $\Delta P_{km}^{X_{TCSC}}$

$$\Delta P_{km}^{X_{TSCSC}} = P_{km}^{reg} - P_{km}^{X_{TCSC,cal}}$$

is the active power flow mismatch for the series reactance; given $\Delta X_{TCSC} = X_{TCSC}^{(i)} - X_{TCSC}^{(i-1)}$ is the incremental change in series reactance; and $P_{km}^{X_{TCSC,cal}}$ is the calculated power as given by equation. The state variable $X_{TCSC}$ of the series controller is updated at the end of each iterative step according to

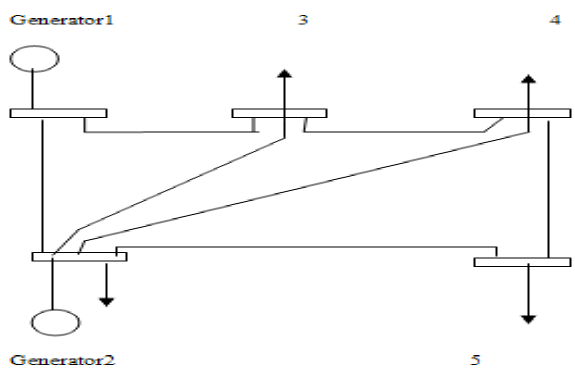
| Bus No. | Vol (P.U) | Generation (P.U) MW | MVAR | Load (P.U) MW | MVAR | Qmin | Qmax |
|---|---|---|---|---|---|---|---|
| 1 | 1.06 | 0.0 | 0.0 | 0.0 | 0.0 | -5 | 5 |
| 2 | 1.0 | 0.4 | 0.0 | 0.2 | 0.1 | -3 | 3 |
| 3 | 1.0 | 0.0 | 0.0 | 0.4 | 0.15 | __ | __ |
| 4 | 1.0 | 0.0 | 0.0 | 0.4 | 0.05 | __ | __ |
| 5 | 1.0 | 0.0 | 0.0 | 0.6 | 0.1 | __ | __ |

$$X_{TCSC}^{(i)} = X_{TCSC}^{(i-1)} + \left(\frac{\Delta X_{TCSC}}{X_{TCSC}}\right)^{(i)} X_{TCSC}^{(i-1)}$$

## IV. System Study

### 5-Bus System

The test system considered here for the analysis using the sensitivity parameter is shown [1] below which is a 5 - bus system with 7 lines interconnected between these buses. The system has 2 generators connected at the buses 1and 2 respectively. The System data corresponding to generators & the line data are given in below;




**Line Data:**

**Bus Data**

| Buses | Resistance | Reactance | Admittance |
|---|---|---|---|
| 1-2 | 0.02 | 0.06 | 0.06 |
| 1-3 | 0.08 | 0.24 | 0.05 |
| 2-3 | 0.06 | 0.18 | 0.04 |
| 2-4 | 0.06 | 0.18 | 0.04 |
| 2-5 | 0.04 | 0.12 | 0.03 |
| 3-4 | 0.01 | 0.03 | 0.02 |
| 4-5 | 0.08 | 0.24 | 0.05 |

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## V. Method for Optimal Location of Facts Devices

Previous studies have utilized dynamic considerations such as improving the stability [1] and damping the oscillations for the placement of the FACTS devices. This paper utilizes static considerations based on the following objectives.Reduction in the real power loss of a particular line-k. $(P_{LK})$ Reduction in the total system real power loss $(P_{LT})$. Reduction in the total system active power loss will reduce or eliminate unwanted loop flows but there is no guarantee that lines will not be overloaded.

**Total system loss sensitivity indices:**

The exact loss formula of a system having N buses is,

$$P_{LT}^{'} = \sum_{j=1}^{N} \sum_{k=1}^{N} [a_{jk}(P_j P_k + Q_j Q_k) + \beta_{jk}(Q_j P_k - P_j Q_k)]$$ Where $P_j and Q_j$ respectively, are the real and reactive power injected at bus-j and $\alpha, \beta$ are the loss coefficients defined by

$$a_{jk} = \frac{r_{jk}}{V_j V_k}\cos(\delta_j - \delta_k) and \beta_{jk} = \frac{r_{jk}}{V_j V_k}\sin(\delta_j - \delta_k)$$ Where

$r_{jk}$ is the real part of the $j-k^{th}$ element of $[Z_{bus}]$ matrix. This total loss if FACTS device, one at a time, is used, can be written as follows (the symbols on the right hand side are defined in equations

$$P_{LT} = \{P_{LT} - (p_{ic} + P_{jc})\} \quad for \;\; TCSC$$

The total system real power loss sensitivity factors with respect to the parameters of TCSC can be defined $b_{ck} = \frac{\partial P_{lt}}{\partial x_{ck}} \Big| x_{c=0}$ Total loss sensitivity with respect to TCSC placed in line-k. These factors are computed using equation at a base load flow solution. Consider a line-k connected between bus i and bus-j. The total system loss sensitivity w.r.t. TCSC can be derived as given below.

$$b_k^s = \frac{\partial P_{LT} \partial P_i}{\partial P_i \partial_{vk}} \Big| x_{ck=0} + \frac{\partial_{LT} \partial P_J}{\partial P_j \partial_{ck}} \Big| x_{ck=0} + \frac{\partial P_{LT} \partial Q_I}{\partial Q \partial_{ck}} \Big| x_{ck=0} - \{\frac{\partial P_{ic} + \partial P_{jc}}{\partial Q_j \partial_{ck}}\}$$ Where

$$\frac{\partial P_{LT}}{\partial P_i} = 2\sum_{m=-}^{N} (a_{im} P_m - \beta_m Q_m) and \frac{\partial P_{LT}}{\partial Q_i} = 2\sum_{m=1}^{N} (\alpha_{im} Q_m + \beta_{im} P_m)$$

$$theterms \frac{\partial P_{LT}}{\partial P_i} \Big| x_{xxk=0}, \frac{\partial P_j}{\partial x_{ck}} \Big| x_{ck=0,}$$

obtained using equations and respectively and are given below:

$$\frac{\partial P_i}{\partial_{ck}} \Big| x_{ck=0} = \frac{\partial P_{ic}}{\partial_{ck}} \Big| x_{ck=0} = (V_i^2 - V_i V_j \cos\delta_{ij}) \frac{\partial \Delta G_{ij}}{\partial_{ck}} \Big| x = 01 - V_i V_j \sin\delta_{ij}) \frac{\partial \Delta B_{ij}}{\partial_{ck}} \Big| x_{c=0}$$

$$\frac{\partial Pj}{\partial_{ck}} \Big| x_{ck=0} = \frac{\partial P_{jc}}{\partial_{ck}} \Big| x_{ck=0} = (V_j^2 - V_i V_j \cos\delta_{ij}) \frac{\partial \Delta G_{ij}}{\partial_{ck}} \Big| x = 01 - V_i V_j \sin\delta_{ij}) \frac{\partial \Delta B_{ij}}{\partial_{ck}} \Big| x_{c=0}$$

## VI. Results & Discussion:

The TCSC model is incorporated in the Newton Raphson Algorithm for load flow studies. The Numerical result for the standard 5 bus network has been presented with and without TCSC and compared. It was found that the TCSC reduces the loss in the lines and allow the lines to flow power within specified limits. The total system loss obtained by using Newton Raphson Method is 0.061P.U& the total loss obtained by optimal placing of TCSC is 0.047P.U.Hence by using TCSC in the network the system losses will be reduced.

| Total System loss without TCSC | Total System loss with TCSC connected at line 2-4 |
|---|---|
| 0.061 p.u | 0.047 p.u |

| Lines from bus i to j | TCSC sensitivity Index |
|---|---|
| 1 - 2 | 36 |
| 1 - 3 | 14 |
| 2 - 3 | 58 |
| 2 - 4 | -174 |
| 2 - 5 | 37 |
| 3 - 4 | 55 |
| 4 - 5 | 6 |

## VII. Conclusion:

In this project a sensitivity based approach for this optimal FACTS location has been developed. The load flows after the

optimal placement suggest that the optimal line power flows are to be so taken that the total system losses and the TCSC are at their optimal value and in this way the power flow through the line can be optimized thus averting the congestion condition.

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